PROCEEDINGS OF SCIENCE

Building the Cosmos in the Antikythera Mechanism

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Abstract

Ever since its discovery by Greek sponge divers in 1901, the Antikythera Mechanism has inspired fascination and fierce debate. In the early years no-one knew what it was. As a result of a hundred years of research, particularly by Albert Rehm, Derek de Solla Price, Michael Wright and, most recently, by members of the *Antikythera Mechanism Research Project*, there has been huge progress in understanding this geared astronomical calculating machine. With its astonishing lunar anomaly mechanism, it emerges as a landmark in the history of technology and one of the true wonders of the ancient world. The latest model includes a mechanical representation of the *Cosmos* that exactly matches an inscription on the back cover of the instrument. We believe that we are now close to the complete machine.

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1 Speaker

1. Ancient Astronomy

Astronomy? Impossible to understand and madness to investigate... Sophocles

Since astronomy is so difficult, I will try to keep everything as simple as possible! As all astronomers know well, the stars are fixed! When the ancients looked at the sky, they saw a number of astronomical bodies that moved relative to the stars. These were the Sun, Moon and planets—the bodies near to the Earth that we call the *Solar System*. They saw them as manifestations of gods and goddesses. This was their *Cosmos*. In this geocentric Cosmos, the movements of such bodies as the planets are not straightforward, with their prograde and retrograde motions. However, they do follow regular, if complex cycles. Some ancient Greek genius conceived the idea that you could mechanize these cycles with gearwheels. It was possible to construct a machine to predict the future—a fundamental step in the history of technology. I want to present a new model of this device that includes the *Cosmos in the Antikythera Mechanism*, based on joint research by myself and Alexander Jones.[1]

1.1 Babylonian Astronomy

The Antikythera Mechanism is Greek but its roots lie in the previous great era of Babylonian astronomy. Over the best part of the first millennium BC, the ancient Babylonians daily watched the skies and recorded their observations in the cuneiform tablets of the so-called *Astronomical Diaries*.[2] It is the longest recorded set of scientific observations in history and it was an extraordinary enterprise. It was driven by omen telling—an early form of astrology—which required predictions to be made of the positions of the astronomical bodies. Much of the project became concerned with identifying repeating cycles that could be used for making these predictions. This was based on period relations, which typically had the form that such-and-such an astronomical cycle was repeated after such-and-such a time period. I would like to give two examples from Babylonian astronomy about the Sun-Moon-Earth system: the *Metonic* and *Saros* cycles.

1.2 Cycles of the Moon

First some definitions for non-astronomers on the cycles of the Moon. The *sidereal month* (27.32 days) is the cycle of the Moon from one star back to the same star—its basic orbital period. The Moon's *nodes* are the points where the Moon's orbit crosses the plane of the Earth's orbit and the *line of nodes* joins these two points. The *draconitic month* (27.21 days) is the month from one of the Moon's nodes back to the same node. It is shorter than the sidereal month because the line of nodes precesses round towards the Moon in a period of about 18.6 years. The Moon's orbit is elliptical: the Moon's closest point to earth is its *perigee* and furthest is its *apogee*. The line joining these two points is called the *line of apsides*. The *anomalistic month* (27.55 days) is the cycle of the Moon from apogee back to apogee. It is longer than the sidereal month because the line of apsides precesses away from the Moon in a period of about 9 years. The *synodic month* (29.53 days)—also called the *lunar month*—is the phase cycle of the Moon relative to the Sun from new Moon back to new Moon. It is longer than the sidereal month because the Moon must catch up with the Sun to return again to new Moon. Remarkably, all of these months—as well as three different types of calendar month—are built into the Antikythera Mechanism.

1.3 Babylonian period relations of the Sun-Moon-Earth system

There are two fundamental period relations of the Sun-Moon-Earth system that come from Babylonian astronomy.[2] The *Metonic cycle* was named after the Greek astronomer, Meton of Athens, but it was known earlier in 5th Century BC Babylonian astronomy: 19 years = 235 synodic months = 254 sidereal months. In ancient times, this identity of lunar months and years was used primarily to build luni-solar calendars. The *Saros cycle* came from 7^{th} Century BC Babylon: 223 lunar months = 242 draconitic months = 239 anomalistic months. It is an eclipse cycle, which works because of the identity of a whole number of lunar months with a whole number of draconitic months. If the Moon is near a node at new Moon (enabling a solar eclipse) then it will be back near the same node after this eclipse period—so there will be a repeat eclipse. Similarly for lunar eclipses. The identity in the Saros cycle with a whole number of anomalistic months means that the repeat eclipse will be very similar, since the Moon will be at the same distance from the Earth and hence the same size relative to the Sun. The Saros cycle generates repeat eclipses for a period between twelve and fifteen centuries before the slight inaccuracies in the cycle means that the repeat no longer happens—it really is an excellent eclipse cycle. One of the main results of our paper in Nature in 2006[3] was that all the surviving gears (except one) in the Antikythera Mechanism can be explained by these two great cycles.

2. The Planets

In all chaos there is a cosmos, in all disorder a secret order... — Karl Jung

What about the planets in the Antikythera Mechanism? These were the other main components of the ancient Greek Cosmos. It is a question that has concerned researchers for more than a hundred years. There are 82 surviving fragments of the Antikythera Mechanism (Fig. 1).[3] What is the "secret order" in this wrecked jigsaw puzzle that reveals the *Cosmos* in the Antikythera Mechanism?

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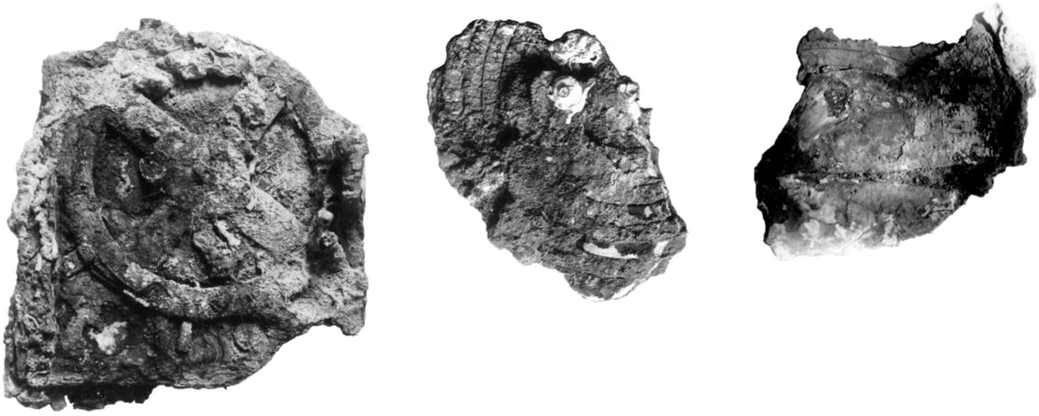
Fig. 1 | Fragments A, B and C of the Antikythera Mechanism imaged with *Polynomial Texture Mapping* (PTM) with specular enhancement. There are 82 surviving fragments in all.

2.1 Albert Rehm

The Antikythera fragments in 1905 were similar to today but have considerably more material—particularly Fragment C (Fig. 2). What did the early researchers suppose about the presence of the planets from these fragments?



Bayerische Staatsbibliothek in Munich,© Dr Hermann Dannheimer

Fig. 2 | Fragments A, B, C of the Antikythera Mechanism in 1905.

For more than a hundred years, there has been controversy about the planets in the Antikythera Mechanism. Albert Rehm was a German philologist, who was the first person to realize that the Mechanism was an astronomical calculating machine. He did much research on the Mechanism but published very little. We only know how advanced his ideas were because of his research notes that are now kept in the Bayerische Staatsbibliothek in Munich[4,5]. Most of his ideas about the gearing and architecture of the Mechanism are wrong, but very often unbelievably prescient. One of his far-sighted ideas was that the Mechanism included a *Planetarium*. He thought that this was displayed on the scales in Fragment B (Fig. 2), which are in the form of five rings—one ring for each of the planets known in ancient times. We are now sure that the scales in Fragment B form part of the Upper Back dial, which is a five-turn spiral with a 19-year 235-month calendar following the Metonic Cycle.[6,7,8] So Rehm was completely wrong about where the planets were shown. Having the right idea and then putting it in the wrong place is a recurring feature of Antikythera research—as is having the right idea and then throwing it away! Much of Rehm's work consisted of speculation in the face of very limited evidence. He often got all the mechanical details wrong but he got the essence right.

2.2 Derek de Solla Price

Derek de Solla Price is the next great name in Antikythera research. He undertook twenty years of research before publishing his great paper, *Gears from the Greeks*.[6] It is the Bible for us all. However, like his predecessor, Albert Rehm, Price got a lot wrong, as well as throwing away some of his best ideas. When Price came to the subject of the planets, he wrote:

> *"...there is a possibility that... a gearing system, now totally vanished... served to exhibit the rotations of all of the planets... If such gearing was to be part of the device it would be most appropriate... just under the front dial plate."*

This time, he didn't get the idea in the wrong place, he simply threw it away and didn't develop the idea at all. This is exactly what we now believe.

2.3 Overall Design of the Mechanism

A co-axial display at the front of the Mechanism with the Sun, Moon and all five planets is the model that we are aiming for—this Cosmos being shown on the front face of the Mechanism

(Fig. 3).[1] The Mechanism was driven by an input on the side via a crown gear that engages with the *Mean Sun Wheel* b1, which rotates once a year at the rate of the mean Sun. This wheel in turn drives gear trains that turn the pointers on the dials. Some of these pointers indicate calendars and rotate at a *constant* rate relative to the turn of the input. Another set of outputs that turn at a *constant* rate are those involved in eclipse prediction—the *Saros* and *Exeligmos* pointers.[3] All the other pointers on the Mechanism showed the ecliptic longitude of the astronomical bodies on the Zodiac scale at the front of the Mechanism. We believe that these pointers all turned at a variable speed in order to follow the variable speed of the astronomical bodies—using epicyclic gearing, coupled with pin and slotted follower devices.

Fig. 3 | Back and Front views of a computer reconstruction of our latest model of the Antikythera Mechanism.

3. The Lunar Anomaly

A key example of variable motion is that of the Moon—the so-called *lunar anomaly*. We know that this anomaly is represented in the Antikythera Mechanism.[3] The first person to consider that the lunar anomaly might be represented was Albert Rehm.[5] Some of his unpublished research notes concern the feature in Fragment C (Fig. 4), which Michael Wright identified as a Moon phase mechanism a hundred years later. Remarkably, Rehm in 1905-06 considered epicyclic gearing for the Moon with a fixed gear on the central axis—exactly what would emerge a hundred years later for the inferior planets. For the Moon, it does not work—so Rehm had got it wrong. Again it was the right idea in the wrong place!

Fig. 4 | Back of Fragment C seen with *Polynomial Texture Mapping* (PTM) with specular enhancement. The Moon phase mechanism runs from the centre of the circular feature in the direction of the 10 o'clock position. The small circular feature at the end was a semi-silvered ball that displayed the Moon's phase.

Price was the next to publish theories on the mechanization of the Moon in the Mechanism, nearly 70 years later.[6] He studied the fragments in depth and thought that he had solved the mechanical structure of the Mechanism. He asserted that the gearing system at the back of the Mechanism (Fig. 5) was a *Differential* that calculated the difference between the Moon's rotation and the Sun's rotation to produce the phase of the Moon. It was a brilliant idea, but it was wrong. The Mechanism does include a differential device to calculate the phase of the Moon: a mechanism discovered by Wright.[9] Right idea by Price, but in the wrong place—yet again! In epicyclic gearing, the axle of one gear is carried round on the face of another gear—a very advanced and subtle form of gearing. Rehm suggested epicyclic gears in the Antikythera Mechanism but not in the right place. However, Price made a critical discovery in identifying an *epicyclic system*, riding on the large gear at the back of the Mechanism, which was part of his *Differential*.[6] He got the function of the gears wrong, but this discovery was nonetheless very significant. It was astonishing to find epicyclic gears in ancient Greece, 1,500 years before they were supposed to have been invented. What did these epicyclic gears actually do?

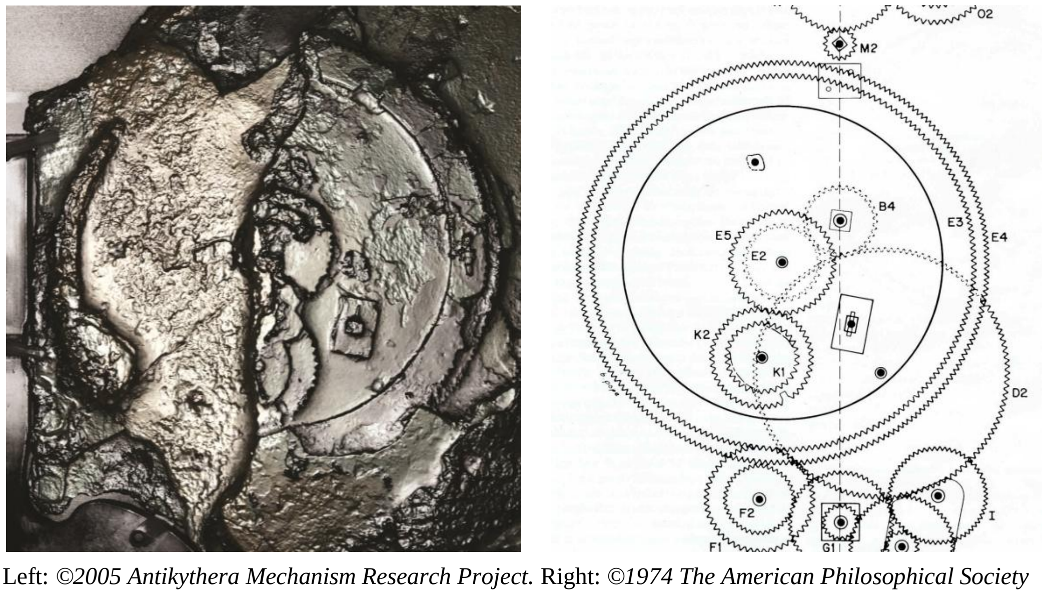


Fig. 5 | *Left: Polynomial Texture Mapping* (PTM) of the back of Fragment A. *Right:* Price's reconstruction of the epicyclic system as a *Differential* from Gears from the Greeks (Price 1974)

In terms of modern astronomy we know that the Moon has an elliptical orbit and this causes a variation in the velocity of the Moon as seen from Earth—the so-called *anomaly* of the Moon. This creates a variation in the Moon's velocity with the period of the anomalistic month, which is about 5½ hours longer than the sidereal month. The ancient Greeks had a geometric theory to explain this variable motion.[2] It is said that they first thought that the Moon—representing the goddess Selene—should have a perfect circular orbit, because gods and goddesses were perfect. But this didn't agree with the reality of the Moon. So they added a second circular rotation to the first—creating an epicyclic motion. The subtlety was that, with correct parameters, the period of the second circular motion relative to the first is the slightly longer anomalistic month. The resulting orbit is an epicycle. It looks like a slightly squashed off-centre circle, whose axis precesses around in a period of about nine years—very similar in form to today's picture of the Moon's orbit as a precessing ellipse. It was a beautiful theory.

3.1 The Epicyclic System

What did Price's epicyclic system—his *Differential*—actually do? This was the most extraordinary result of the research that we published in our paper in Nature in 2006.[3] This paper was the first fruit of new scientific investigations of the Antikythera Mechanism, carried out in 2005 by the *Antikythera Mechanism Research Project* (AMRP) in association with the National Archaeological Museum in Athens. *Polynomial Texture Mapping* (PTM)[10] was undertaken by a team from Hewlett-Packard, led by Tom Malzbender; and *Microfocus X-Ray Computed Tomography* (X-ray CT)[11], by a team from X-Tek Systems (UK), led by Roger Hadland. The first technique revealed fine surface details in the fragments and the second looked inside them in high-resolution 3D.

The gearing system at the back of the Mechanism consists of a large gear e3 with 223 teeth, to which is attached a ring gear e4 with 188 teeth. On the face of e3 are two epicyclic gears k1 and k2, one in front of the other. These mesh with two gears at the centre of e3 to complete the epicyclic system. At first glance, it appears that there are only two small gears in the system. It is to Price's great credit that he identified four gears, as we can see in our X-ray CT data. Two X-ray "slices" just a millimetre apart reveal the four gears: in one slice, e5 and k1; in the second slice, e6 and k2 (Fig. 6).

3.2 Wright's discarded observation

Study of the epicyclic gears k1 and k2, with an earlier X-ray study using *linear tomography*, led to an absolutely crucial observation by Michael Wright. Since the early days after the discovery of the Antikythera Mechanism, it had been noticed that there is a slot in k2. Price thought that it was evidence that the gear had been repaired, but Wright had a much more important insight. He saw that k1 had a pin on it and this engages with the slot on k2. You might say that this looks like an absolutely useless device, since the gears will simply turn at the same rate but Michael Wright made another fine observation. He saw that the gears turn on eccentric axes: this makes a critical difference to the resulting motion (Fig. 6). Michael Wright had no idea what this device was doing there—so he dismissed it as irrelevant for the Antikythera Mechanism. Right idea, thrown away again!

3.3 The Pin-and-Slot

The effect of the eccentric mounting of the gears is highly significant.[3] The pin gear k1 turns at a constant rotation and drives k2 via the slot (Fig. 6). The effect of the eccentric axes is that the driven slot gear k2 sometimes lags behind the pin gear k1, when the pin is near the outside of the slot and sometimes ahead, when the pin is near the inside of the slot. If the gears were not mounted epicyclically, then the period of this variation would be the same as the input period, namely the sidereal month. The designer of the Mechanism knew that this would not model the Moon's anomaly correctly: the period of variation must be the anomalistic month. So he took an extraordinary step: he mounted the pin-and-slot epicyclically to subtly change its period of variation. He arranged for the large gear at the back of the Mechanism to be turned at exactly the right rate—the difference between the sidereal month rotation and the anomalistic month rotation, with a 9-year period. In this way, the pin-and-slot mechanism induced a variation, which is geometrically equivalent to the ancient Greek *Epicyclic Theory of the Moon*.[3] Following the output up through the Mechanism results in a pointer following the variable motion of the Moon on the Zodiac dial at the front.

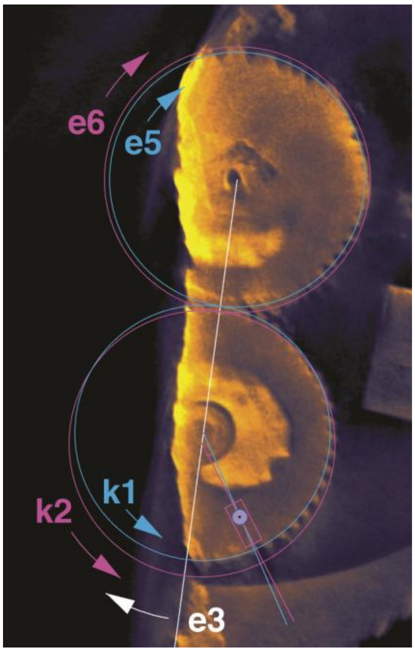


Fig. 6 | Small gears of the epicyclic system, with the pin-and-slot, mounted epicyclically on e3.

It is a beautiful and elegant solution to the lunar anomaly. It is very hard to understand how the designer devised this extraordinary conception. It is not the direct way of modelling the deferent and epicycle model, but it is a very economic solution—just four gears, with an epicyclic pin gear and an epicyclic slot gear on eccentric axes (Fig. 7). A work of genius.

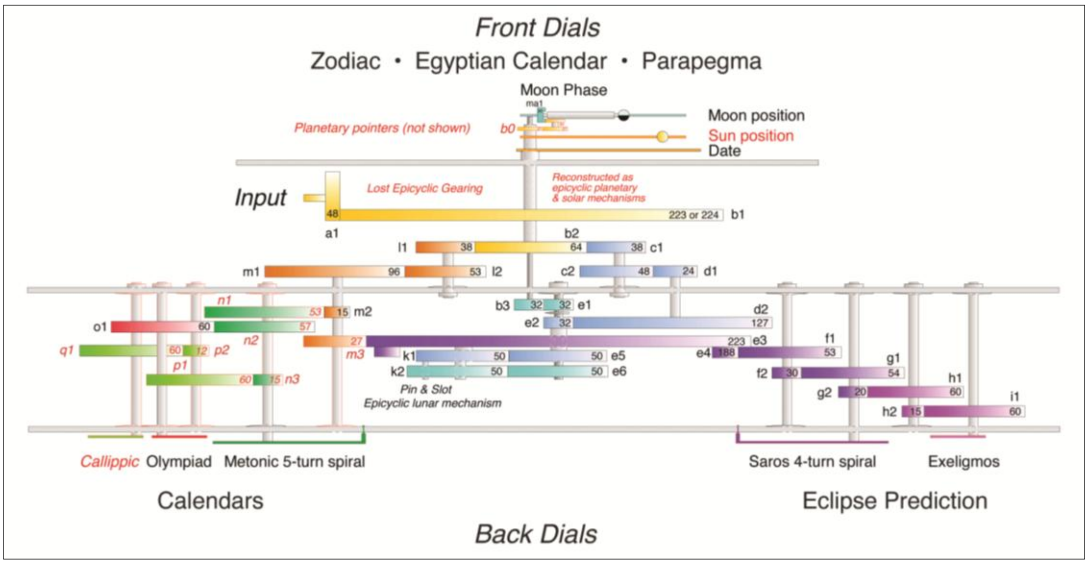


Fig. 7 | Schematic gear diagram of the Antikythera Mechanism, showing its complexity.

4. Evidence for the Planets

The pin-and-slot device in the lunar anomaly mechanism creates a precedent for looking at the mechanization of other variable motions in the Antikythera Mechanism—particularly the planets. The evidence that the planets were included in the Antikythera Mechanism is now overwhelming. It comes from four sources, which will be examined in turn.

4.1 Classical quotations

First some remarkable evidence from the lawyer, politician and orator, Cicero.[6] In 212 BC, the Romans finally succeeded in their siege of Syracuse and Archimedes was killed by a Roman soldier. Cicero writes that the victorious general, Marcellus, took home with him two astronomical "globes" that had been made by Archimedes and *"...nothing else out of the great store of booty captured."*[6] One of these globes was seen around 70 years later in the house of the grandson of Marcellus.

> *"... the famous Sicilian had been endowed with greater genius than one would imagine it possible for a human being to possess... this... globe... on which were delineated the motions of the sun and moon and of those five stars which are called wanderers... (the five planets)... Archimedes... had thought out a way to represent accurately by a single device for turning the globe those various and divergent movements with their different rates of speed..."*
>
> Cicero, De re publica, 54 – 51 BC

This inscription sounds exactly like the Antikythera Mechanism. Cicero mentions that the device was made from bronze but he doesn't say that it had gears—though I think that it is very likely that it did. It is our first piece of evidence that such mechanisms were around in ancient times and included all five planets. However, it is obviously a second-hand account, since the reported sighting was around a century before Cicero wrote about it. Cicero also writes about another machine:

> *"...the Orrery recently constructed by our friend Posidonios, which at each revolution reproduces the same motions of the sun, the moon and the five planets that take place in the heavens every day and night..."*
>
> Cicero, De natura deorum, 45 BC

In this case, it is probable that this is a first-hand account. Cicero was a student of Posidonios, who was head of the Stoic school of philosophy in Rhodes and a considerable scientist. So it is very likely that Cicero did actually see this device. Again it included all the planets. Both these quotes give us a strong historical background for believing that all five planets were included in the Antikythera Mechanism.

4.2 Inscriptions

In *Scientific American*,[12] Derek de Solla Price (Price 1959) wrote:

> *"On the upper (back) dial the inscriptions... might well present information on the risings and settings, stations and retrogradations of the planets known to the Greeks (Mercury, Venus, Mars, Jupiter and Saturn)."*

We now know that the Upper Back dial is a 19-year Metonic calendar dial with 235 lunar months[6,7,8]. The inscriptions on this dial are month names and year numbers—so Price was wrong. However, there is an inscription on the Mechanism that exactly fits Price's description. Fragment G was part of the Front Cover. Price could only read a few text characters on Fragment G because the surface is so worn. However, with our X-ray CT we can read many text characters. Yanis Bitsakis and Agamemnon Tselikas read more than 900 new characters from our new data.[3] Recently we have read even more. This is work-in-progress and will be published in a forthcoming series of papers about the inscriptions, coordinated by Alexander Jones, so I will not comment in detail about the inscription. However I can say that the content is about the planets and their "*...risings and settings, stations and retrogradations".* Again, Price had exactly the right idea in the wrong place!

Recently, Alexander Jones has looked again at the Back Cover inscription (Fig. 8) (not the Front Cover inscription described in the previous paragraph)—in particular, part of the Back Cover that survives in mirror text imprinted onto Fragment B.[1] He has found traces of the names of all five planets in this inscription. They are mentioned in a specific order that reflects the ancient Greek geocentric Cosmos. Indeed the word *Cosmos* itself is included in the inscription. The inscription describes how each planet moves in a "circle" which is above the circle for the previous planet and each planet appears to have be represented by a "little sphere" that moved through the circle. We believe that this is a description of the front of the Antikythera Mechanism as a geocentric Cosmos with the planets displayed in a schematic way as little spheres moving through concentric circles.

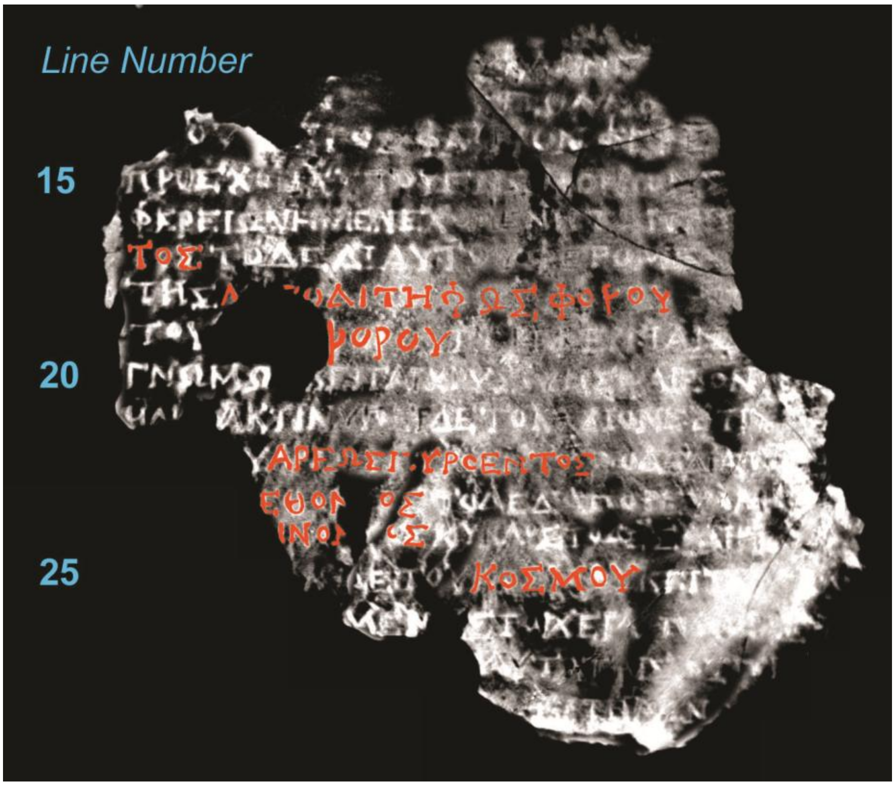


Fig. 8 | A composite image of several X-ray CT slices through Fragment B, showing the Back Cover inscription. Planetary names (some incomplete) for all five planets and the word *Cosmos* are highlighted in red.

In summary, the Front Cover describes the synodic periods of the planets and the Back Cover is a description of how they were displayed on the Front Dials in an ordered ancient Greek geocentric Cosmos. In general, what we read in the inscriptions is reflected in the gears and dials—so we can be very confident that the planets were displayed on the Mechanism.

4.3 Astronomical Theory

So how would the planets have been mechanized in the Antikythera Mechanism? The prevailing theories of the planets in the 2nd century BC were, like the lunar theory, based on simple epicyclic models, combining two constant circular rotations.[2] These theories had been developed by Apollonios of Perga and his contemporaries in the late 3rd and early 2nd centuries BC.[2] Let me take Venus as an example. A large circle rotates at the rate of the Mean Sun. Attached to its circumference is an epicycle, with a pin on its circumefernce representing the planet. It turns at the right rate so that the planet satisfies its period relation. Here I will use the simple period relation from Babylonian astronomy that Venus goes through 5 synodic phases in 8 years. The theory very nicely models the prograde and retrograde motions of the planets: if the planets had circular orbits, it would be an exact geocentric model of the Solar System. In reality it is hopelessly inaccurate, because it fails to properly track the irregular retrograde arcs that the actual planets follow, but no better theory was available at the time.

5. Mechanical Evidence & Models

5.1 Modelling the Planets

For an inferior planet like Venus, this theory can easily be mechanized.[13,14,15] There is a fixed gear at the centre with 50 teeth and this meshes with an epicyclic gear with 80 teeth, which is carried round at the rate of the mean Sun by another gear—modelling the Babylonian period relation for Venus. There is a pin on this gear, which engages with a slotted follower that rotates at the centre. The resulting variable motion is carried by a tube to the output pointer. Using these ideas, there was a lot of research in the period 2000–2003 on how the planets could be included in the Mechanism.[13,14,15] All of these papers included interesting ideas, but the work of Michael Wright was for the most part the most advanced and I want to focus on this. Wright not only published his result, but also built physical models. When I first saw his model with all five planets and eight co-axial pointers on the front dials, I was astonished. I thought this sort of mechanical sophistication in ancient Greece was impossible, but I have since changed my mind.

5.2 Wright's Models

Though Wright's models are groundbreaking, I don't believe that they are plausible models of the Antikythera Mechanism. In all of the versions of Wright's model that includes the planets, they are mechanized in essentially the same very complex way, though Wright prefers the description "extensive".[15] The inferior planets are not placed directly on the spokes of the large wheel b1 at the front—as would seem natural—he places their axes between the spokes. What is the point of making a wheel with spokes, if you then have to fill in the gaps to carry the bearings of several gears? Wright has also included the superior planets—again in a very complicated way with seven or eight gears for each planet, powered by an awkward auxiliary axle at the side. The whole arrangement is unnecessarily cumbersome and not in the spirit of economy and elegance that we know from the rest of the Mechanism. These models also seem to abandon the surviving evidence of the pillars on b1 (Section 5.3). A final criticism is that all of this gearwork is accommodated in a large box protruding at the front. Because of research on the star calendar (*parapegma*) inscription on the Front Plate (publication forthcoming), we are confident that the front of the Mechanism was flat to include these inscriptions, so Wright's box cannot be correct. I believe that the evidence from the surviving data strongly suggests that the Mechanism was designed by a mathematician. My own approach has been to try to find an elegant mathematical solution to the problem—particularly for the superior planets.

5.3 Evidence from the *Mean Sun Wheel*

The front of Fragment A shows the large four-spoked gear b1, called the *Mean Sun Wheel* (Fig. 9). On the spokes of this wheel are a number of evident holes and flattened areas.[1] As Wright has proposed, these are surely the traces of an extensive epicyclic system of gears mounted on this wheel.[16] At the centre is a squared boss that is suitable to carry fixed gears, like the fixed gear of the Venus mechanism. On the right-hand side, where the input crown wheel is located, there are three pillars—one long pillar and two short pillars and they are fixed to the circumference of b1.

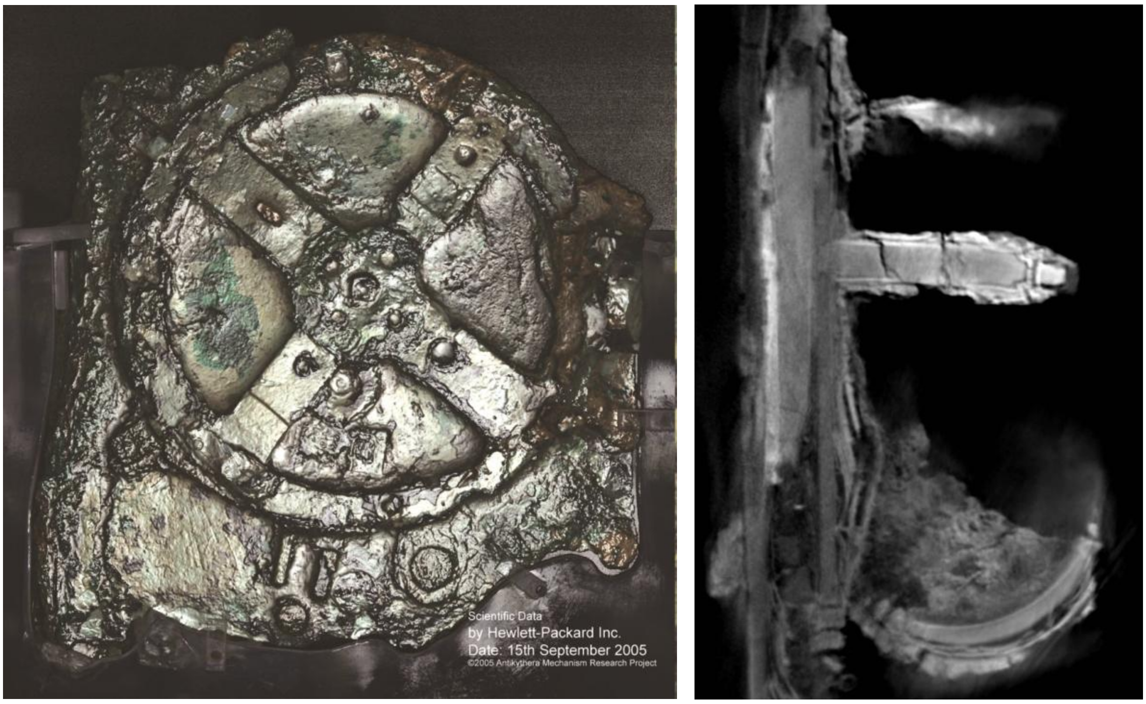


Fig. 9 | On the left, a close-up PTM of the Mean Sun Wheel, b1. On the right an X-ray CT slice, showing two of the three surviving pillars on b1. At the bottom is the crown gear a1.

The pillars are such a prominent feature of the wheel that they demand an explanation. Round the periphery of the wheel, there is evidence that shows that there must originally have been four short and four long pillars. X-ray CT slices through the pillars reveal shoulders and pierced ends. It is clear that they were designed to carry plates that were fixed to the pillars with pins. These plates will play an essential role in our model.[1]

6. Building the Cosmos

We can now reconstruct the Mean Sun Wheel, with its bearings and eight pillars. What functions did these features have? The Moon is already spoken for by the lunar anomaly mechanism at the back, so the likely candidates must be the Sun and the planets. I want to make a reconstruction of the lost gearing on this wheel. Because of the missing evidence, this must of necessity be a conjectural reconstruction—so we must be careful not to make too many dogmatic claims about it.

6.1 Inferior Planets & Sun

First the mechanisms for the inferior planets and the Sun.[1] These are relatively easy because these bodies all “go with the Sun” (Fig. 10). A suitable mechanism for Mercury will have tooth counts that exactly reflect the period relation for the planet. Here I have chosen 104 synodic cycles in 33 years because it means that the bearings match those on the spokes. It is quite a good period relation, but I am not happy with it because it is not known from Babylonian astronomy. For Venus, we use 5 synodic cycles in 8 years from Babylonian astronomy. In this model, the Sun shares its fixed gear with Venus and needs an equal epicyclic gear, separated by an idler gear. At every stage my aim is to match the gears to apparent bearings and fittings on the spokes. The pins are carried by circular plates, following Michael Wright's scheme. These engage with slotted followers, which carry their outputs via tubes to pointers.

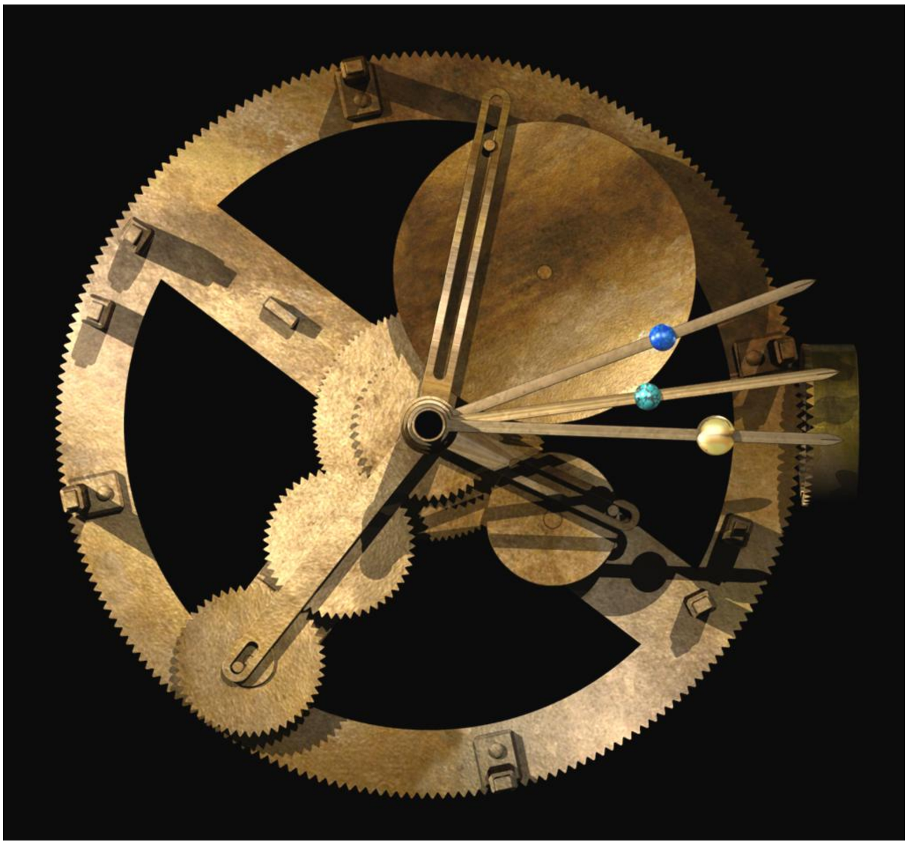


Fig. 10 | The Mean Sun Wheel b1, with the Venus mechanism at 1 o'clock, the Mercury mechanism at 4 o'clock and the solar mechanism at 7 o'clock.

The other parameter that follows the mean Sun is the *Date*, which must be rigidly attached to the Mean Sun Wheel. For this we use the short pillars, to which we add a plate, which carries a tube attached to the Date pointer for the Egyptian calendar on the front of the Mechanism.[6]

6.2 Superior Planets

So now we need to add the superior planets.[1] For these, we use the long pillars, to which I am going to attach a conjectural annular plate to carry the superior planet mechanisms. I shall call this the *Superior Planet Plate* (SPP). The inferior planets—Mercury and Venus—were fairly easy; it was the superior planets that I always found problematic. How to include them in a simple way? Originally, I had serious doubts that all five planets could be incorporated into the Mechanism in harmony with the gearing that we already knew. I had failed to find any simple solution after several years of attempts. When Alexander Jones told me about his work on the Back Cover planetary inscription, I had to make another attempt on this problem. The solution then came fairly quickly. It was astonishing to discover that the same gearing structure that worked for the Moon's anomaly would also work for the superior planets (Fig. 11).

For Mars (and similarly for the other superior planets) the tooth counts of the two 69-tooth gears have no special meaning—they simply mean that the gears fill the space between their two centres. With suitable parameters for the pin distance and the inter-axial distance of the two epicyclic gears, this exactly models the epicyclic theory of Mars. Just four gears that work in exactly the same way as the lunar anomaly mechanism to model the prograde and retrograde motions of the planets. It completely stunned me that this scheme works.

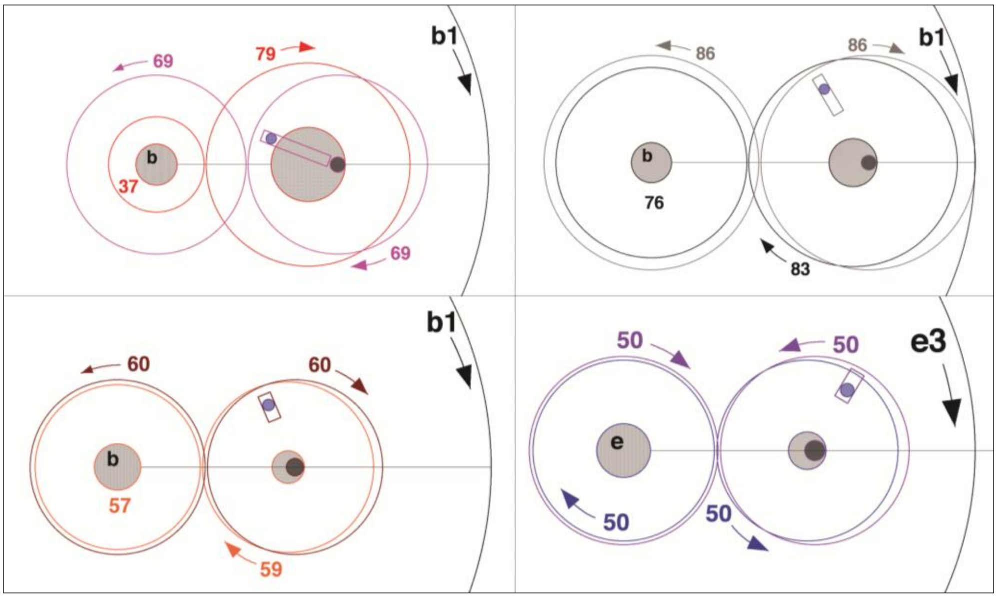


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Fig. 11 | Diagrams of the new superior planet mechanism with the lunar anomaly mechanism for comparison. *Top row:* Mars, Jupiter. *Bottom row:* Saturn, Moon. All the planetary mechanisms work on the same principle, with tooth counts exactly reflecting the period relations from Babylonian astronomy. For Mars, with 37 synodic periods in 79 years: there is a 37-tooth *fixed gear* on axis b; this meshes with a 79-tooth *pin gear*, with a pin on its face and carried epicyclically on b1; the pin engages with a slot on a 69-tooth *slot gear*, also epicyclic on b1 but on a different axis; the slot gear engages with another 69-tooth *output gear* on axis b, which carries the output to the Zodiac dial. The similarities between the lunar anomaly and the Saturn mechanisms are striking.

After we had written our draft publication, we discovered that at around the same time Christián Carlos Carman from Jim Evans' group in Puget Sound, came up with the same idea for the superior planets.[17]

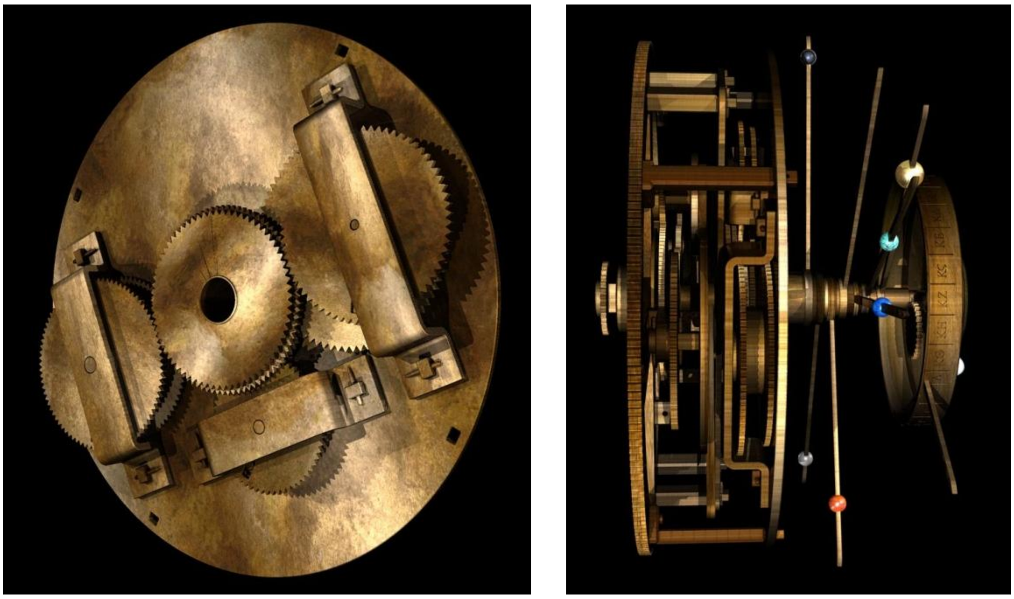

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Fig. 12 | *Left:* Superior planet plate with *Mercury* at 2 o'clock, *Saturn* at 5 o'clock and *Jupiter* at 8 o/clock. *Right:* The planet module with the planetary and solar anomaly mechanisms in the space

defined by the long pillars. The pointers include marker beads at different distances to indicate place in the ancient Greek Cosmos. The Moon pointer and phase device complete the assembly.

My aim is to include mechanisms for all the planets inside the space defined by the long pillars on b1 at the front of the Mechanism.[1] With similar spacing as the surviving gearwork, the inferior planets take up just under half this space, so it is natural to include the superior planets attached behind the Superior Planet Plate (Fig. 12). All the superior planets fit neatly at 90° angles, with the levels of gearing and outputs designed not to interfere with each other.

Fig. 13 | Exploded computer reconstruction of the new *Cosmos* model of the Antikythera Mechanism.

I believe that there is compelling evidence that this is essentially how the ancient Greeks designed the Antikythera Mechanism (Fig. 13). The similarity of the new superior planetary mechanisms to the lunar anomaly mechanism is persuasive. This model explains much of the puzzling evidence on b1—the bearings as well as the long and short pillars. It all fits exactly and appears to be right. The evidence that all five planets were included in the Mechanism is now overwhelming. We cannot be certain exactly how this was accomplished because of lost data. However, I believe that there is enough evidence to suggest that our Cosmos model is a convincing reconstruction of the Mechanism. It is the first model since the Mechanism was found in 1901 that matches all the surviving evidence.

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